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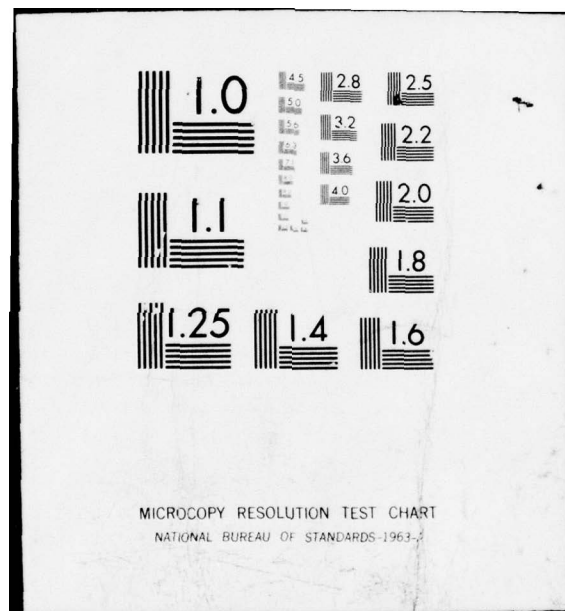
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INFRARED THERMOGRAPHY OF BUILDINGS

An Annotated Bibliography

Stephen J. Marshall

March 1977



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report summarizes a review of the current literature on the new subject of infrared thermography of buildings. Infrared thermography of buildings (IRTB) uses a thermal imaging scanner to detect heat loss, structural defects, moisture, and other anomalies in building envelopes. Photographs of the imagery called thermograms provide hard copy documentation of faults detected. Thirty-four references are abstracted, covering research and development, roof moisture surveys, and qualitative/quantitative field surveys. The readily ob-		

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tainable sources were chosen for their practical approach to providing potential users who are not scientifically oriented with an opportunity to quickly grasp the value of this new technology.

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P R E F A C E

This report was prepared by Stephen J. Marshall, Physical Science Technician, of the Physical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by DA Project 4A161101A91D, Task 03, In-House Laboratory Independent Research, Work Unit 242, Thermography of Test Wall Sections.

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INTRODUCTION

Infrared Thermography (IRT) of buildings is a recently developed use of thermal imaging scanners for the purpose of detecting heat loss/gain in buildings.

As fuel costs rise and supplies dwindle, the conservation of heat in buildings is becoming of vital concern. Many buildings were constructed in the days of cheap and abundant fuel, when insulation and thermal integrity were not primary considerations. Today, these buildings and future buildings must be adapted to more modern standards of energy conservation.

The first step in reducing heat losses is, of course, identifying the source of waste and infrared thermography of buildings (IRTB) does just that. The operator, called a thermographer, can locate a heat loss problem by scanning the building with his camera. The infrared scanner produces a black and white output on a screen similar to a TV set. The images, indicating heat, vary in intensity from bright white to dark gray. These images are photographed, and the photos, called thermograms, can be taken back to the laboratory to be analyzed in detail.

Purpose

It is the purpose of this annotated bibliography to help the reader unfamiliar with IRTB to quickly grasp the value and usefulness of this technology. This use is presently not widespread, due to the very high cost of instrumentation, the lack of experienced personnel (especially those able to interpret thermograms), the fact that IRTB is still in the process of development and refinement, and the general apathy toward the energy crisis. This bibliography gives the serious reader enough background information to decide what to pursue further and where to pursue it.

Scope and organization

The literature was searched with the following constraints: all articles needed to be in English or translated into English, easy to obtain, and not too esoteric or erudite to be of immediate practical use. The bibliography is organized alphabetically by author. Although the subject of IRT of the total building envelope does break down nicely into the following order, it was felt that there are not enough serious articles at this time to use such an outline.

Ground survey

1. Inside Survey (GIS)
2. Outside Survey (GOS)
3. Roof Moisture Survey (GRM)

Airborne survey

1. Heat Loss Survey (AHL)
2. Roof Moisture Survey (ARM)

(QL) QUALITATIVE SURVEY - Tells us where to correct.

(QN) QUANTITATIVE SURVEY - Justifies spending money.

Bands

1. 2 to 5.5 μm , Midwave (MWIR)
2. 8 to 14 μm , Longwave (LWIR)
3. Other

Equipment currently used for IRTB

1. AGA Model 680
2. AGA Model 750
3. Barnes Model T-101 (InSb)
4. Barnes Model T-101 (PbSnTe)
5. Barnes IAX-8
6. Bendix M²S
7. ERIM M7
8. Inframetrics Model 510
9. Texas Instruments B-310
10. AN/AAS-18

Impressions from the literature

If the installations surveyed in the following abstracts are typical of the U.S. nation as a whole, then we have hardly scratched the surface on the subject of energy conservation. If the success enjoyed by these surveys could be magnified on a national scale, then IRTB is a means by which to make present energy sources last until the end of the century when new energy sources are predicted to come on line.

The technology reported in this bibliography needs to be optimized in terms of cutting costs of surveys, lowering prices of equipment, making more equipment and trained personnel available, and conducting more research into the technical problems that exist at the present time. However, the basic state of the art has been achieved and IRTB seems destined to be widely used by bankers, brokers, and building managers, as well as by officials charged with the responsibility of enforcing new energy conservation regulations.

ABSTRACTS

1. AGA INFRARED SYSTEMS (1976) *Spotting heat loss from buildings - Thermovision*. AGA Corporation, 550 County Ave., Secaucus, New Jersey.

This manual is an introduction to an important new aspect of technology that is the most significant development in the science of heat detection in the last 25 years: the use of an infrared camera system to inspect structures for heat loss and heat gain. This technology, known as infrared thermography, is the tool that can reveal where and how much energy is being wasted in both residential and business establishments. The energy efficiency of buildings can be increased selectively at minimum expense and with maximum effect, through the use of thermographic inspection to select sites for improvement. Without thermographic inspections, efforts to improve the thermal integrity of buildings are little more than guesswork.

- 2a. BJORKLUND, J., F.A. Schmer, and R.E. Isakson. (1975) *A report on the use of thermal scanner data in an operational program for monitoring apparent rooftop temperatures*. *Proceedings of the Tenth International Symposium on Remote Sensing of Environment*. p. 1437-1446, Environmental Research Institute of Michigan, Ann Arbor, Michigan, (1975).
- 2b. BJORKLUND, J., F.A. Schmer, and R.E. Isakson. (1975) *Aerial thermal scanner data for monitoring rooftop temperatures*. SDSU-RSI-75-11. Remote Sensing Institute. S.D. State Univ., Brookings, South Dakota, and Central Tel. & Utilities Corp. CENGAS Div., Lincoln, Nebraska. 5 thermograms, 20 p. Same Abstract - expanded text.

CENGAS, a division of Central Telephone and Utilities Corporation, in cooperation with the Remote Sensing Institute, South Dakota State University, is using airborne thermal scanner data to monitor relative rooftop temperatures. Four Nebraska communities and one South Dakota community were surveyed by the Remote Sensing Institute for CENGAS. Thermal scanner data were converted to a film format and the resultant imagery has been successfully employed by CENGAS. The program places emphasis on heat losses resulting from inadequate home insulation, offers CENGAS customers the opportunity to observe a thermogram of their rooftops, and assists home-owners in evaluating insulation needs.

3. BOWMAN, R.L. and J.R. Jack. (1977) *Application of remote thermal scanning to the NASA Energy Conservation Program*. Lewis Research Center, NASA, Cleveland, Ohio, Report no. E-9017. NASA Report no. NASA TM X-73570, 24 p.

Airborne thermal scans of all NASA centers were made during 1975 and 1976. The remotely sensed data were used to identify a variety of heat losses, including those from building roofs and central heating system distribution lines. Thermal imagery from several NASA centers is presented to demonstrate the capability of detecting these heat losses remotely. Many heat loss areas located by the scan data have been verified by ground surveys. At this point, at least for such energy-intensive areas, thermal scanning has proven to be an excellent means of detecting many possible energy losses.

This report presents a brief introduction to infrared thermal scanning primarily for the nontechnical user, discusses its application to the detection of energy losses in energy-intensive installations, and presents some typical experimental results. Results of ground surveys based on the remotely sensed data are also presented.

4. BROWN, N.B. (1971) *Heat leakage detection in a building using an infrared radiometer camera system.* Geophysical Institute, University of Alaska, College, Alaska, 3 thermograms, 10 p.

The surface temperature distributions on the exterior walls of a University of Alaska building were measured by mapping the intensity of thermally emitted radiation with an infrared radiometer camera system. Heat leakage and thermal bridging in the structure were readily observed and detailed examples are given. The use of this technology is suggested for future thermal evaluation studies in building research and construction.

5. BROWN, G. and B. Pettersson. (1976) *Detecting and analyzing building insulation defects by the thermography method.* Swedish National Authority for Testing, Inspection and Metrology, P.O. 5608, S-11486, Stockholm, Sweden, 35 thermograms, 38 p.

Thermography uses an infrared camera. Cold portions of a depicted surface are seen as dark on an oscilloscope screen or on photographic paper. When this method is used in Sweden for building inspection cameras sensitive to radiation in the wavelength range of 2-5.6 μ m are utilized for determining the temperature distribution over wall and floor surfaces. By taking pictures (thermograms) in a building which has to be inspected, and by comparing them with pictures from a correctly constructed building of the same design, it is possible to assess insulation defects (poor insulation work, air leakage, moisture damage).

Rules for interpretation of thermograms are drawn up at the Swedish National Academy for Testing, Inspection and Metrology. The climatic and other conditions necessary for getting reliable results are investigated. This method is now used as a routine instrument for building inspection. A proposal for an international standard in the field of thermography has been submitted to the International Standards Association.

- 6a. BURKHART, C.H. (1976) *Infrared thermography of buildings. Civil Engineering Technical Report. CETR-1, U.S. Coast Guard Headquarters, Washington, DC, 9 thermograms, 27 p.*
- 6b. BURKHART, G.H. (1976) *Infrared thermography of buildings. Coast Guard Engineer's Digest. CG-133, no. 192, p. 9-23, 4 thermograms.*

Recent international concern over energy management and utilization has led to the accelerated development of practical applications of certain techniques which had previously been of concern only to researchers. One of these techniques is the ability to detect infrared radiation using super-cooled semiconductors. Through pioneering efforts in Sweden, the concept of infrared thermography of buildings has developed into a powerful tool for energy management.

The key word is "tool." Infrared thermography provides valuable information with a depth, speed, and quality never before possible, but it does not by itself solve energy management problems.

It is a "qualitative" tool. It will tell you exactly where heat losses are occurring, and will give you a very good idea of the relative magnitude of the loss but it will not enable you to accurately quantify the loss.

This report discusses the theory of thermography and infrared radiation, explains how detection is accomplished and why it is indicative of temperature, tells how to survey a facility and outlines the nature of the information such a survey will provide, and generally describes the tool to the extent required by the Coast Guard facility manager.

7. DAEDALUS ENTERPRISES (1976) *VANSCAN continuous mobile thermography: Daedalus Enterprises, Inc., P.O. Box 1869, Ann Arbor, Michigan.*

Heat losses cost energy dollars and money on energy can be saved if the losses can be located. VANSCAN detects energy loss problems and gives a permanent picture of where they occur, plus a comparative scale of their thermal severity. The savings are both immediate and long-range by using the thermogram to resolve major problems and plan future maintenance programs. A typical "case in point" is illustrated by a university complex that experienced annual energy losses from wall-mounted radiators. The two white areas on the thermogram indicate temperatures in excess of 43°F where two of the radiators were mounted on the inside wall. The two high heat loss areas on the outside brick wall registered 52°F with an air temperature at 30°F! This is typical of many normally undetected heat losses that occur around campuses which, although small on an individual basis, add up to a large energy dollar waste collectively over each heating season.

The VANSCAN Thermograms are continuous strip prints, not frames, created as the vehicle containing the IR scanner moves around the facility to be surveyed. The scanner has a resolution of 1 in.² at a range of 100 ft and is equipped with a gyro stabilization system to correct distortions caused by instability. The measurements are recorded on magnetic tape, and through the

use of patented data processing methods, precisely temperature calibrated, color-coded positive strip prints are extracted. A series of thermogram image strips are produced for detailed inspection.

8. GROT, R. (1976) *Application of thermography for evaluating effectiveness of retrofit measures*. National Bureau of Standards, Washington, D.C.

Retrofit measures in single family dwellings are considered an important part of the overall U.S. energy conservation program. Thermography was used to evaluate the effectiveness of a number of different retrofit measures normally available to the resident-owner. In this study, a group of townhouses were selected which, it was suspected, would benefit by commonly available retrofit measures. These houses were thermographically inspected before and after various retrofit measures were taken to increase the tightness of the dwelling. These included caulking of windows, doors, and exterior cracks as well as increasing attic insulations from R-11 to R-30. Thermography was found to be an effective tool for evaluating these retrofit measures which decreased the energy consumption by about 30%.

9. HARDING, J. (1976) *Thermography: Visual proof of an insulation job well done*. Roofing, Siding, Insulation Magazine, p. 64-66, 2 thermograms, November.

Harding Insulation of Minneapolis, Minnesota, utilizes an infrared inspection service (Energy Conservation Consultants, Inc., Bloomington, Minnesota) to stimulate its sales and convince homeowners that they are getting sufficient and proper insulation. Minnesota was the first state to pass a bill for "Design and Evaluation Criteria for Energy Conservation in New Buildings" which calls for all new homes to be insulated to prescribed performance standards. A suggestion for the use of thermographic inspection of all foamed-in-place urea formaldehyde insulation installations has been issued by the Building Code Division of Minnesota Department of Administration. The city of Rochester will not approve similar installations unless and until they are thermographically inspected.

10. HAZARD, W. (1976) *A multi-staged thermal survey of housing*: Hazard and Associates, Austin, Texas.

Three broad areas of concern must be examined for a definitive analysis of energy conservation in buildings - those factors which define the nature of the enclosure, those related to thermostat setting and occupant life style, and those related to equipment efficiency and heat recovery devices.

In general, energy transfer through a residential enclosure is a function of the type and quantity of materials used, the quality of construction and certain design features. The factors of importance are: 1) insulation, 2) infiltration, 3) glass, 4) orientation and external shading, and 5) building shape and thermal mass.

This preliminary study of heat gain/loss in Garland, Texas, focused on loss through convection, radiation and conduction from glass and from an infiltration through small openings in joints, around doors and windows, under baseboards, etc. Glass and infiltration aspects of a structure are shown to be the major determinants of the energy performance of building enclosures.

Particularly, the analysis concerned insulation and infiltration factors which have in the past proved to be difficult to determine and elusive to document.

The principal means of estimating loss from 22,577 structures was to observe thermal "flaring" from photographic records of an airborne radiometer.

In the Texas Instruments B-310 radiometer, energy is received by the scanner from the ground, is focused on cryogenic-cooled detectors, converted to light through the use of a light-emitting diode, and by means of a mechanically-coupled recorder exposes the photographic film in the film magazine. The film is moved at a rate proportional to the velocity and height of the aircraft, producing a continuous photographic record of the radiant energy detected.

By utilizing the AGA Thermovision system on the ground, relative surface temperature variations of $\pm 2^{\circ}\text{C}$ were calculated, thereby revealing the presence of even the slightest cold air infiltration around casings and jams, under baseboards, or through joints in the walls and ceilings. Insulation problems due to hot air leakage and cold air infiltration were thus identified.

Energy loss from each of 24 test houses is classified as "severe," "high," "moderate," and "low" by scoring the energy performance of a structure along several dimensions. Conclusions about overall heat loss in Garland, Texas (a suburb of Dallas) were that approximately 2% of the single-family structures in the city exhibit noticeable loss. Eight percent of the multi-family units and nearly 90% of the commercial and industrial buildings show a similar significant degree of heat loss/gain due to infiltration problems.

11. HEADLEY, R.B., R.J. Larsen, G.M. Goldberg, and R.L. Boyd. (1977) *Infrared thermography requirements study for energy conservation. Final Report no. ARI-ADD-77-1, Prepared for U.S. Energy Research & Development Administration, 20 Massachusetts Avenue, Washington, D.C., 4 thermograms, 138 p.*

Aerodyne Research, Inc.'s contract with the U.S. Energy Research and Development Administration requires that a study be made to identify users (and their needs) of IR instrumentation that may be applicable in the measurement of heat gain and/or losses from buildings and to identify research and development and demonstration opportunities. The work flow diagram for this study is shown and is intended to provide the following information:

- Identify present and potential uses and users of infrared thermographic technology.
- Identify presently available IR thermographic instrumentation, techniques, and services, and determine how well it can serve the users and uses identified above.
- Identify technical opportunities for research, development, and demonstration (RD&D) on new IR thermographic technology that will better serve the users and uses identified above.

Under a subcontract to Aerodyne, the NAHB Research Foundation, Inc. has analyzed the building sector requirements, identified the user measurement requirements, and has provided cost guidelines for instrumentation. This work is described in Section 2.

Section 3 contains an analysis of the constraints, requirements, and limitations of measurable parameters. This analysis provides the basis against which IR instrument survey was conducted and reported in Section 4.

The building sector requirements study indicates the general satisfaction of the user community with the use of IR thermography for qualitative evaluation of heat loss from buildings. It is pointed out that qualitative evaluation requires resolvable temperature differences of 1 to 3.5°C. Cryogenic thermographic scanning systems as they exist today have this capability but have been used, for the most part, for qualitative heat loss evaluation. If 1°C resolution systems can be used to provide the same qualitative information, then the reduced resolution may allow for instrumentation with a 5:1 or better cost saving. The community use should increase significantly.

Wider use of IR thermography will require education and training. Demonstration programs are needed to develop the art of thermographic interpretation for wider community use. As a part of this effort, it will be necessary to demonstrate that thermography using 1°C instruments provides essentially the same qualitative information as do 0.1°C instruments.

Absolute temperature measurements for quantitative code enforcement and for laboratory use require 0.1°C to 0.35°C accuracy. This can be done in IR measurements from the inside of buildings. Outside measurements are limited to 1°C uncertainty, however. Accuracies better than this require a temperature computation and instrument calibration that will account for spectral wavelength properties of the atmosphere, background, and building materials. Spectral emissivities of building materials must be known to the order of 0.5%. A measurement program is required to determine the limitation in emissivity measurement and to evaluate the effect of the nonuniform IR background that is reflected off the structure into the IR thermographic camera. Recommended R&D includes the need to:

1. Measure spectral radiation parameters such as emissivity that now limit the usefulness of quantitative temperature measurements.

2. Develop very low cost electro-optical thermal imaging devices for qualitative heat loss evaluation.
 3. Accomplish spectral optimization of electro-optical thermal imaging cameras for precise quantitative measurements of heat loss.
 4. Develop infrared liquid crystal and semiconductor photographic sensor material and cameras with very low cost thermographic picture potential.
12. HESS, R.A. (1975) *Aerial heat sensing detects hidden energy waste. Airconditioning & Refrigeration Business, October, 1 thermogram, 2 p.*

Thermal scanning from a helicopter offers the energy manager an opportunity to study energy use and waste over his entire facility at one time. It gives him a profile of the interaction of the various buildings and operations in his plants and offers an opportunity to set priorities for energy savings.

For instance, one survey showed a tremendous heat loss from a warehouse. The owners asked themselves if the warehouse really needed to be heated since its only occupant was an occasional fork-lift operator. Another survey found electrically heated steps that ran continually, rather than only during periods of ice and snow. The 16.5-kW-steps were wasting 56,336 BTU/hr. In another case, it was found that a small steam leak of $\frac{1}{2}$ -inch diameter under 90-lb pressure over a 12-month period at a cost of \$4 per 1000 lb of steam would cost about \$14,000.

A typical college campus survey costs between \$7,000 to \$12,000, but steam leaks detected waste more than that in energy costs in less than a year.

13. HURLEY, C.W. and K.G. Kreider. (1976) *Applications of thermography for energy conservation in industry. National Bureau of Standards, Dept. of Commerce, Washington, DC, Report no. NBS TN-923, 11 Thermograms, 31 p.*

Infrared thermography has been developed as a tool to measure the temperature of various types of surfaces. Notable applications include thermal detection of diseases such as cancer and circulatory problems in human beings, aerial land mapping of hot surfaces to detect thermal pollution and geological formations, and remote scanning of buildings to detect heat losses. More recently, infrared scanning has been used to detect defects in high amperage electrical connections, transformers, and steel processing furnaces in industrial environments.

It was the intent of the NBS IR program to build on these technologies to assist energy conservation engineers to assess heat losses in industrial plants. IR teams from the NBS Center for Building Technology had previously used the equipment to survey heat losses in buildings where the

IR camera was found to be particularly useful in detecting infiltration problems, missing insulation, and construction defects. The intent of this project was to survey furnaces and heating systems in addition to electrical and mechanical systems to find areas suggesting energy conserving actions. This qualitative survey has been found to be an excellent method to detect heat losses in unit process equipment and auxiliary systems. This survey method described in this paper was carried out in 15 industrial plants in order to develop a methodology and examine the feasibility of the approach.

In addition to the qualitative survey, quantitative data were gathered by calibrating the temperature of the "hot spots" uncovered in the survey. This information was very useful in developing priorities and estimating the magnitude of the heat loss due to a given defect.

14. *Inframetrics, Inc. (1976) Thermographic heat loss survey of the Given/Rowell Medical Building Complex at the University of Vermont. Inframetrics, Inc. 225 Crescent St., Waltham, Massachusetts, 7 thermograms, 4 p.*

The survey was conducted at night on 5 and 6 April 1976 with normal inside temperatures and an outside temperature of 3°C. Some observations were as follows:

1. As much as 50% of the energy consumed is expended through the exhaust louvers.
2. Areas on the roof of the heat exchanger penthouse indicated heat loss and need repair.
3. Hot spots on some windows indicated that the air deflectors on the heat exchangers below the windows are directing the air blast against the windows and should be reoriented to direct the heat back into the rooms.
4. Heat was being lost through a window behind the elevator.

The survey suggested that \$1213/year could be saved by correcting these deficiencies. Energy loss calculations from a thermograph in terms of cost savings per year are described in an appendix.

15. *KORHONON, C., W. Tobiasson, and T. Dudley. CRREL roof moisture survey: Pease Air Force Base, Buildings 33, 116, 122 and 205. U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) Hanover, NH. 4 Thermograms, 14 p.*

During the night of 14-15 October 1976, the roofs of Buildings 33, 116, 122 and 205 at Pease AFB were surveyed with an infrared camera. Infrared photographs (thermograms) were obtained on light-colored (hot) anomalies on each roof. Suspected moisture-caused anomalies were outlined with white spray paint. The following day, samples were taken to verify infrared findings, conventional photographs were obtained, problem areas were examined for visual signs of distress, and dimensions were taken to locate the anomalies on plans of each roof. Water contents of all samples were subsequently determined by oven drying at 110°F. This report covers the above work and also includes information on Building 116 obtained on 10 September 1975 as part of the roof research program that CRREL is conducting for the Facility Engineering Directorate of the Corps of Engineers.

16. LINK, L.E. (1976) *Demonstration of a new technique for rapidly surveying roof moisture*. Miscellaneous Paper M-76-14, MESL, U.S. Army Engineer Waterways Experiment Station (WES), P.O. Box 631, Vicksburg, Mississippi. Final Report prepared for U.S. Air Force, SAC Hdqrs., Offutt AFB, Omaha, Nebraska, 49 p.

The results of this study demonstrate the potential of the combined thermal IR-nuclear moisture meter roof survey technique. Application of the technique at Dyess AFB, Texas, resulted in the detection of roof areas with entrapped moisture on 5 of the 128 buildings surveyed. Airborne thermal IR imagery proved to be a very effective means of identifying roof areas with potential entrapped moisture. Some false alarms were created by air vents on smaller buildings; however, prior knowledge of the position of the vents (i.e. during the examination of the imagery) would probably reduce this problem considerably. Not all the questions were answered. Information is needed to define the usefulness of the technique as a function of climatic conditions and roof types. In addition, more data are needed to help define the optimum time for acquiring thermal IR imagery for roof moisture surveys.

17. LLOYD, J.M. (1975) *Thermal Imaging Systems*. New York: Plenum Press, 11 thermograms, 445 p.

In the early days of thermal imaging technology, strong competition kept design practices closely guarded secrets. Now that the field has expanded, many of these procedures have become standard, and an integrative, cohesive assessment is required. That is the aim of this book.

This volume, a dynamic introduction as well as a ready reference for experienced practitioners, sets forth the essential design conventions which form the basis for forward-looking infrared (FLIR) practice. The work not only provides a useful compendium of previously unpublished or obscurely published literature, but also offers a systematic treatment of fundamental methods for thermal imaging system engineering. It includes more than 250 references and extensively details every major thermal imaging process - from thermal energy generation to visual psycho-physics.

This book is intended to serve as an introduction to the technology of thermal imaging and as a compendium of the conventions which form the basis of current FLIR practice. Those topics on thermal imaging which are covered adequately elsewhere are not treated here, so there is no discussion of detectors, cryogenic coolers, circuit design, or video displays. Useful information not readily available is referenced as originating from personal communications.

18. LYNCH, J. (1976) *Practical application of infrared inspection of residential dwellings*. Energy Conservation Consultants, Inc., Hopkins, Minnesota.

Energy Conservation Consultants have been offering infrared inspection services to residential home owners and insulation contractors for nearly a year. Using this technique, the user of this service can be provided with an on-site qualitative analysis of his energy losses. The basic inspection, interior or exterior, usually takes one hour or less. Interior inspections are becoming increasingly the trend although exterior inspection is still important for identifying gross defects. Most high energy losses produce significant temperature variations allowing for easily identifiable detection. Variations in building materials and weather conditions must always be taken into account but these do not inhibit practical inspection from being cost-effective.

- 19a. MARSHALL, S.J., and R.H. Munis. (1974) *An infrared thermographic analysis of Dartmouth College, Winter 1974. Part I: Thermogram inventory.* CRREL Technical Note. (unpublished) 114 thermograms, 30 p.

During March-April 1974, 32 buildings on the Dartmouth College campus were surveyed at night with a Barnes Mobile Infrared Camera. One-hundred-fourteen thermograms are reproduced in this report with a listing of the operator's comments and other data.

- 19b. MARSHALL, S.J. and R.H. Munis. (1976) *An infrared thermographic analysis of Dartmouth College, Spring 1976. Part II: Thermogram inventory.* CRREL Technical Note. (unpublished) 67 thermograms, 18 p.

During March 1976 selected buildings on the Dartmouth College campus were resurveyed using an AGA Model 750 Thermovision System. Sixteen buildings were resurveyed and 64 thermograms taken.

- 19c. MARSHALL, S.J. and R.H. Munis. (1976) *An infrared thermographic analysis of Dartmouth College. Part III: Building photographs, building energy usage data, weather data, campus map.* CRREL Technical Note. (unpublished), 50 p.

Building photographs, building energy usage data and weather data are compiled in support of Parts I and II of the Dartmouth College Infrared Survey.

20. MARSHALL, S.J. and R.H. Munis. (1976) *An infrared thermographic telephoto analysis of the Dartmouth 175-ft smokestack during a steeplejack inspection.* CRREL Technical Note. (unpublished) 15 thermograms, 19 p.

During April/May 1976 the Dartmouth 175-ft unlined smokestack was inspected by a steeplejack for the purpose of determining the extent of deterioration and recommending repairs.

This afforded an excellent opportunity to survey the smokestack at the same time with an infrared thermographic camera fitted with an infrared telephoto lens. The outside stack was also photographed with a telephoto lens to afford the opportunity of a close visual examination.

The thermograms were compared with the photographs and the chimney inspection report. It was concluded that dry mortar and stairstep cracks can be detected but that further research needs to be done in order to refine the technique.

21. MUNIS, R.J. (1975) *Thermography: A new way to profit from the energy crisis*. Hicksville, New York: Exposition Press, Inc., 2 thermograms, 45 p.

This book outlines an innovative, existing technology that promises to become, within the next five years, the single most important technology for effecting energy conservation in each and every building across the United States - infrared thermography.

Infrared thermography uses an infrared camera system to detect heat radiated from an object, and can be employed to pinpoint the locations of wasteful and costly heat loss and gain in every conceivable type and size of building. The book emphasizes that a short-term solution to the Energy Crisis can be obtained only by adequately insulating every building in this country - and infrared thermographic inspection is the only method by which the effectiveness of a building's insulation can be monitored.

The author gives a detailed explanation of this technology and its potential as a new and lucrative business (i.e. how a building heat loss inspection service can be established and profitably operated), and illustrates that no new technologies are required to assist homeowners, businessmen, and industrialists.

Photographs of the AGA Thermovision infrared camera system are included as well as thermograms ("heat pictures") showing costly heat loss.

22. MUNIS, R.H., R.H. Berger, S.J. Marshall, and M.A. Bush. (1974) *Detecting structural heat losses with mobile infrared thermography. Part I: Description of technique*. CRREL Research Report 326, AD 001549, 9 thermograms, 12 p.

A method to assess quickly the insulation effectiveness of buildings using mobile infrared thermography has been developed at CRREL. In contrast to the infrared thermography done in Sweden, this method concentrates on obtaining useful data by measuring the outside surface temperature of structures. This report outlines the basic principles involved in these measurements, and discusses field measurements and the inherent advantages of infrared thermography. Typical thermograms are presented in the appendices.

23. MUNIS, R.H., R.H. Berger, S.J. Marshall, and M.A. Bush (1975) *Detecting structural heat losses with mobile infrared thermography. Part II: Survey of Pease Air Force Base, Portsmouth, NH. CRREL Research Report 338, AD A012117, 32 thermograms, 29 p.*

During the winter of 1973-74 a mobile infrared thermography system was used to survey housing units and base facilities at Pease Air Force Base, Portsmouth, New Hampshire. This report provides both qualitative and quantitative evidence regarding heat flow out of the eave vents of these housing units. Calculations indicate that a significant amount of heat is being lost in this manner due to inadequate attic (cap) insulation. Possible evidence of incomplete ventilation could explain the presence of condensation in the housing units. Analyses of thermograms are presented to show the possible existence of low and high pressure areas around a structure and how they relate to heat loss.

24. MUNIS, R.H., R.H. Berger, S.J. Marshall, and M.A. Bush (1975) *Detecting structural heat losses with mobile infrared thermography. December 1975. Part III. CRREL Research Report 348, AD A020375. 8 thermograms, 9p.*

During the winter of 1973-74 a mobile infrared thermography system was used to survey the CRREL building at Hanover, New Hampshire. This report provides a description of excessive heat losses at several locations around the building. This report also discusses the need to carefully monitor meteorological conditions before starting a survey of a building exterior to determine if solar radiation decay from the building surface might interfere with thermographic analysis by masking the heat emanating from within the building.

25. MUNIS, R.H., S.J. Marshall, and M.A. Bush (1976) *Detecting structural heat losses with mobile infrared thermography. Part IV: Estimating quantitative heat loss at Dartmouth College, Hanover, New Hampshire. CRREL Report 76-33. 4 thermograms, 9 p.*

During the winter of 1973-74 a mobile infrared thermography system was used to survey campus buildings at Dartmouth Collge, Hanover, New

Hampshire. This report provides both qualitative and quantitative data regarding heat flow through a small area of a wall of one brick dormitory building before and after installation of aluminum reflectors between radiators and the wall. These data were used to estimate annual cost savings for 22 buildings of similar construction having aluminum reflectors installed behind 1100 radiators. The data were then compared with the actual savings which were calculated from condensate meter data. The discrepancy between estimated and actual annual cost savings is explained in detail along with all assumptions required for these calculations.

26. MUNIS, R.H., C.H. Burkhurt, and R. Riley. (1976) *Infrared thermography at the U.S. Coast Guard Academy. CRREL Technical Note (unpublished), 77 thermograms, 40 p.*

On 25 and 26 February 1976, Coast Guard Academy facilities were surveyed using the AGA Thermovision System 750. The main purpose of the survey was a field evaluation of the AGA system. The survey time and scope were limited to those necessary to obtain a reasonably good idea of the capabilities and limitations of the AGA system; however, almost every Academy structure was surveyed from two or more sides, and this report gives a good general idea of the relative thermal efficiency of each building.

The following pages contain thermograms of various facilities, paired with normal photos taken some time later from about the same position. Thermograms in this report have been enlarged about two times. "Normal" photos were taken with a Kodak pocket instamatic.

The page facing the thermograms and photos describes the facility and makes certain observations deduced from an analysis of the thermographs.

Almost all of these thermograms were taken at night, between 2100 and 0200, when the temperature was about 45°F. This was necessary during the survey period because of the unusually warm (mid-60's), sunny days. The difference between outdoor and indoor temperature should be greater than 30°F for effective thermography. Further, the absorption of solar energy by masonry and concrete surfaces completely distorts the true thermal picture; it is also possible that reradiated solar energy will affect thermography if many hours have not passed since sunset.

A single number in the upper left hand corner or at the top edge of each thermogram (usually "2" or "5") indicates the nominal differential thermal scale shown. This number is in degrees Celsius, and represents the approximate difference in temperature between "very dark" (representing cool) and "very light" (representing warm). The left hand scale is used in the "isotherm mode" which is explained within the report.

27. MUNIS, R.H., S.J. Marshall, and P.E.J. Vogel. (in preparation) *Pinpointing locations of excessive heat loss in ten selected office buildings, Concord, New Hampshire. CRREL Report.*

Pursuant to a contract negotiated between the State of New Hampshire and the U.S. Army Cold Regions Research and Engineering Laboratory, a heat loss survey to pinpoint excessive heat losses was made of 10 selected buildings in Concord, New Hampshire. Three thermographers, Dr. Richard H. Munis and Stephen J. Marshall of CRREL and Paul E.J. Vogel of the U.S. Army Materials and Mechanics Research Center (AMMRC) performed the survey using an AGA Thermovision infrared camera system. Following the heat loss survey, a walk-through inspection was made of all buildings. The combination of data from both inspections was used to make recommendations for corrective actions.

In order to make a comparison of the 10 buildings, the concept of structural thermal efficiency is introduced in this report. It is strictly arbitrary and somewhat subjective, with the sole purpose of trying to assign a priority to those buildings that were estimated to have the worst heat losses and, therefore, the highest potential for maximum dollar savings to the State of New Hampshire. The ranking of the ten buildings is as follows (the lowest structural thermal efficiency, or worst heat loss, is #1; the highest structural thermal efficiency, or least heat loss, is #10):

1. Department of Public Health
2. State House Annex
3. State House
- .. 4. State Highway Garage
5. Supreme Court
6. State Library
7. John O. Morton Building
8. Department of Fish and Game
9. Health and Welfare Laboratory
10. Legislative Office Building (Old Section)

Detailed reports on each of the 10 selected buildings are presented.

28. PALJAK, I. and B. Pettersson (1972) *Thermography of buildings*.
Svensk Byggtjarst, Box 1403, S-11184 Stockholm, Sweden. 700
thermograms, 56 p.

Thermography of Buildings is the first comprehensive manual (in the world) which describes the theory and techniques employed in using an infrared camera to determine insulation defects in buildings. An IR-camera produces a thermal image (thermogram) which immediately reveals points of air leakage and insulation defects in the structure under examination. Thermography is a convenient nondestructive test method which may be expected to assume extensive application and considerable economic significance.

An introductory section describes the method of operation of an IR-camera and the theory underlying the interpretation of thermograms produced by this camera.

The main section describes the technique of thermography and lays down practical rules for work on the site. Conditions during measurement

and the accuracy of the method are discussed in view of the possible sources of error and the desired results. Proposals are put forward for the interpretation of the thermograms produced.

The document is concluded by a 56-page catalog containing over 700 typical thermograms, many of them in color. The catalog is divided into two sections, one which contains typical thermograms of the most common wall designs built strictly according to specifications, and the other the same walls with constructional and insulation defects of general occurrence. Four different types of wall are described in this way, two framed cladding panels, one sandwich wall and one light-weight concrete wall.

It is expected that this manual with its catalog of typical thermograms will become a standard work of reference, and it may also come to have legal significance in checking building defects. For instance, thermography is eminently suitable for use in the event of dispute to provide a ruling as to whether a structure satisfies the specified insulation requirements. During the inspection of buildings, the manual will be found to be an essential work of reference for quick and correct interpretation of thermograms obtained with the IR camera.

Developers and building enterprises may expect to save large sums of money by the introduction of thermography as an integral part of the building inspection process.

29. *SAMPSON, R.E. and T.W. Wagner (1976) Application of infrared technology to buildings. Environmental Research Institute of Michigan, Ann Arbor, Michigan.*

During the 1975-76 winter heating season, ERIM conducted studies to test the applications of airborne and ground-based infrared technology to the requirements for energy conservation in buildings. Quantitative airborne data of the City of Ypsilanti, Michigan, were collected and processed to identify roof temperatures and subsequently, using a thermal model, to interpret ceiling insulation status. Environmental factors which were found to influence the relation between roof temperature and insulation include interior and sky temperatures, roofing materials, and the pitch and orientation of the roof. A follow-up mail survey established the ability to identify insulated houses from the airborne infrared data.

Ground-based thermovision surveys provided detailed information concerning construction and insulation conditions of small buildings. In particular, interior thermal images showed the location of wall and ceiling structural members, heat ducting, and sources of air infiltration. In application to a large steam heating system of the University of Michigan, the ground based thermal imagery revealed defective steam traps, with a projected energy savings valued at approximately \$35,000.

30. SMITH, I.E., M. Flanagan, and S.D. Probert. (1976) *The effect of uncertainties in the emissivity on thermal loss estimates from buildings and structures*. School of Mechanical Engineering, Cranfield Institute of Technology, England.

The use of infrared thermography as a means of quantitatively determining the heat loss from buildings requires that temperature differences of only a few degrees between the surface of the fabric and ambient be measured, and therefore accuracies of only tenths of a degree are called for.

In order to achieve such a degree of precision in the interpretation of thermograms it is shown that values of the fabric emissivity must be known to at least 1% if the emissivity is in the range 0.95 - 1, and considerably more accurately if the emissivity is less than this.

An apparatus has been designed and fabricated which enables emissivities to be determined with a high degree of accuracy, and experimental results for a range of building materials are reported.

31. Stainton, W.D. (Ed.) (1976) *Proceedings of Canadian Symposium on Thermography and Energy Conservation*, Ryerson Polytechnical Institute, Department of Architectural Technology, Toronto, Ontario.

Following is a list of nine reports and their respective authors. Included in the proceedings of the "Canadian Symposium on Thermography and Energy Conservation" held in Toronto, December 1976, are: (1) "The Role of Thermography in the Projects of the Ontario Ministry of Energy" - Dr. Ian Rowe, Ontario Ministry of Energy. (2) "The Ministry of Natural Resources Flyover Project" - Garth Lawrence, Ontario Centre for Remote Sensing. (3) "Application of Infrared Technology to Buildings" - Robert E. Sampson, Environmental Research Institute of Michigan. (4) "Practical Applications of Thermography to Quantifying Heat Losses from Buildings" - Dr. Richard H. Munis, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. (5) "Application of Thermography for Evaluating the Effectiveness of Retrofit Measures" - Dr. Richard Grot, Building Services Section, National Bureau of Standards. (6) "Applications of Thermography to Buildings in Sweden 1968-1976" - Dr. Ivar Paljak, Swedish Standards Association. (7) "Industrial Infrared Surveys for Energy Conservation" - Dr. Kenneth Kreider, Office of Energy Conservation IAT, National Bureau of Standards. (8) "Thermography in Steel Plant Operations Maintenance and Research" - James D. Fleischer, Research Centre, Republic Steel. (9) "Preventative Maintenance in Chemical Industry" - Carl Nielson, Material and Mechanical Research and Development, Dow Chemical.

32. TANIS, F.J., R.E. Sampson, and T.W. Wagner. (1976) *Final report, thermal imagery for evaluation of construction and insulation conditions of small buildings*. 116600-12-F. Office of Energy Conservation and Environment, FEA, Washington, DC 20461. Contract no. CO-04-50233-00. Environmental Research Institute of Michigan, Ann Arbor, Michigan, 78 thermograms, 56 p.

Final technical results are presented on the use of airborne and ground infrared imaging techniques to gain information on heat loss from buildings. A portable infrared device has been used to examine the interior and exterior of residences. Example thermograms presented show the kind of construction defects and insulation problems which can be analyzed from ground surveys. Aerial survey imagery is shown and analyzed with residential questionnaire results. The applicability of new and commercially available infrared (IR) technologies to construction and insulation practices of small buildings has been studied. Knowing that many residential and commercial structures are not well constructed from an energy standpoint, the central question is whether infrared devices provide useful information in identifying building energy losses. Within the constraints imposed by the technology and the complexity of actual heat transfer mechanisms, this study attempts to illustrate the applications and limitations of infrared technology.

The approach taken in this study was to look at a variety of structures from the standpoint of heat transfer characteristics and to illustrate with specific examples the value of infrared imagery in identifying heat losses. While this study does not cover every aspect of infrared sensing, it does provide sufficient background for the non-specialist to interpret thermal images of buildings.

The first part of this report provides background material on heat transfer analysis, building construction, applications of instrumentation, and methodology on data collection and analysis. The second part describes the collection of infrared and supporting data for thermal imagery analysis of small buildings.

33. TOBIASSON, W. and C. Korhonen. (1977) *CRREL roof moisture survey, Pease Air Force Base Hospital*. CRREL Special Report. 1 thermogram, 12 p.

On 8 October 1975 the roofs of Pease AFB were surveyed with a portable infrared camera. Infrared photographs (thermograms) were obtained and white spray paint was used to outline areas expected to be wet. No problems were detected on the high central roof, but several were uncovered on the roof above the first floor. The following day four, 3-in. samples were taken through the membrane and insulation in two wet areas and two dry areas as indicated by the infrared survey. The wet insulation had water contents of 508% and 132% (expressed as the weight ratio of water to dry insulation). The dry samples had water contents of 13% and 1%. A plan

view of the roofs with "wet" and "suspected wet" areas is given, and the location and water content of samples taken at that time are also shown.

Because most wet areas are located around a drain, it is quite likely that water has entered the roof at the drains. The overall condition of other portions of the hospital roof appeared mottled when viewed with the infrared camera. It is possible that this is an indication that much of the roof insulation contains small amounts of water.

Subsequent roof cuts by the New York District have verified that the "suspected wet" area in the southeast portion of the roof is also wet. In April 1976 a breather vent was installed in this area and the three other "wet" areas. It was hoped that the vents would dry the wet insulation and restore the roof to its desired condition.

34. *VOGEL, E.J. (1974) Infrared NDT and energy conservation. Army Materials and Mechanics Research Center, Watertown, Massachusetts, 14 thermograms, 14 p.*

The development of infrared equipment for nondestructive testing has been refined to the point that instruments are available to detect any loss of energy that can be expressed in terms of heat flow to the surface or airborne particulate matter. A brief introduction to infrared NDT will be given, followed by a number of thermograms of insulation problems, leaking steam valves, stack losses, extravagant cooling, random leaks, etc. It will be shown that periodic plant checks by infrared will not only contribute to the national energy conservation effort but will also result in significant operational economies.

ADDED IN PROOF

- BURCH, D.M., T. Kusuda, and D.G. Blum (1977) An infrared technique for heat loss measurement. National Bureau of Standards, Report NBS TN-933, 44p.*

This paper describes a newly developed technique for measuring heat-loss rate utilizing an infrared television system. A device called a heat-flow reference pad was developed that makes it possible to measure quantitatively the heat-loss rate through the surface of a building without the need for a conventional heat-flow meter to be mounted on the surface. Technical considerations for the design of a heat-flow reference pad are presented. The infrared measurement technique predicted heat-loss rates in the laboratory and field within approximately 12%.

CARNEY, J.C., T.C. Vogel, E.R. Love and G.E. Howard (1977)
*Interagency energy and environmental survey. Geographic
Information Systems Division, U.S. Army Engineer Topographic
Laboratory, Technical Report, 15 thermograms, 58p.*

The results of this survey demonstrate the feasibility of using multispectral remote sensing techniques, whereby an U.S. Army Facility Engineer can reduce the number of man-hours currently required for energy and environmental assessments. These include detecting building heat losses and deteriorated insulation invisible to the human eye, performing electrical inspections under full operating loads, and monitoring environmental conditions on a successive annual basis. This survey method, developed during the winter and summer of 1976, employs a handheld infrared imaging device, color and color infrared aerial photography, and thermal infrared imagery.

The thermal infrared imagery is used in conjunction with color aerial photography to detect energy losses and defective roof insulation. This imagery should be obtained during the winter season on a 2-year cycle, 2 to 3 hours after sundown at a scale of 1:4,000. and 1:20,000.

The color and color infrared photography aids the Facility Engineer in the analysis of the thermal infrared imagery, provides a source of information for establishing a baseline of environmental conditions for future comparison, and monitors potential environmental problem areas. This photography should be obtained simultaneously on a 4-year cycle, between the hours of 1000 and 1500, at scales of 1:10,000 and 1:20,000. During the first cycle, the photography should be obtained in conjunction with the winter thermal infrared flights and repeated during the summer season. The photography and infrared imagery should always be acquired under clear, unobstructed skies.

The handheld infrared device is employed to determine the exact locations of energy losses and roof areas underlain with wet insulation after they have been detected on the aerial infrared imagery. The device can also be used to survey electrical distribution systems, detect heat losses through building walls, and monitor steam lines.

MUNIS, R.H. and S.J. Marshall (1977) *Qualitative assessment of window heat loss using infrared thermography. CRREL Technical Note (unpublished). 6 thermograms, 6 p.*

An experiment was performed to evaluate four identical side-by-side windows in the same room. They consisted of 1) a single pane glass, 2) a single pane glass with storm sash (air space $1\frac{1}{2}$ in.), 3) a single pane glass with 6-mil clear plastic (air space $1\frac{1}{2}$ in.), and 4) insulating glass ($\frac{1}{4}$ -in. air space).

Conclusions were that either glass or plastic performs equally well as the second glazing, but that the important factor is the size of the enclosed air space. The $\frac{1}{4}$ -in. insulating glass did not appear to perform much better than the single pane glass. Infiltration around window casings was also studied.

MUNIS, R.H. and P.E. Vogel (1977) Excess heat loss study of the Harold F. Scott School, Warwick, Rhode Island. CRREL Special Report (in preparation), 7 thermograms, 6 p.

The Scott School was surveyed with an infrared camera during November, 1976. It is a single story 14-sided polygon built in 1965. The unusually shaped roof was viewed with a fire department aerial tower. Pockets of subsurface moisture were observed. Conduction through the steel rafters was evident.

The single-pane glass heat loss appeared to be about as large as the roof loss because the source of heat is under the windows. Up to 16°F temperature differences were found between classrooms. Vandalism was a factor in deciding not to incorporate double glazing.

Recommendations are included in this study, based on thermographic analysis and walk-through inspections. This analysis represents the first known attempt by public administrators to recognize the potential of infrared thermography and use it to survey publicly owned buildings through the Federal Technology Transfer Program.

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